Life Cycles of Magnetic Fields in Stellar Evolution

A White Paper Submitted to the Astro-2010 Decadal Survey

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Endorsed by the Topical Group on Plasma Astrophysics of the American Physical Society

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1 Introduction

Understanding the structure and evolution of the stars is a great triumph of 20th century Astrophysics. But this has also revealed a plethora of unsolved problems associated with the magnetization of stellar matter. These include magnetic mediation of star formation, rotational structure and evolution of main sequence stars, the origin of stellar magnetism itself, stellar mass loss, coronal activity, etc. The death of stars and their after-life as compact objects presents a variety of additional puzzles whose answers are also illuminating for understanding similar phenomena in galaxies harboring supermassive black holes. Questions of wide interest for the coming decade are those related to the death of massive stars — supernovae (SNe) and the remnants they leave behind (neutron stars and black holes), including the relativistic outflows from neutron stars and the disks around black holes, and the impulsive jets inferred in GRBs, both those associated with SNe and those perhaps powered by merging neutron stars. All of these phenomena are directly or indirectly tied to the magnetic fields embedded in the stellar material. Thus all are illuminated by the incorporation of plasma physics into astrophysics, the realm of *Plasma Astrophysics*.

Prospects for further progress in Plasma Astrophysics in the next decade are very bright, and are due to recent and anticipated advances in theory, simulations, and the advent of laboratory plasma-astrophysics experiments.

An over-arching theme in plasma physics as applied to astrophysical objects is the *life cycle of magnetic fields*:
(1) Their origin: How are they produced and amplified?
(2) Their active life: how do they interact with the plasma and affect the dynamic behavior of various astrophysical systems?
(3) and finally, their destruction: how are they destroyed (dissipated) and what is the fate and observable signatures of the released magnetic energy?

These themes come up repeatedly in various astrophysical situations and have direct observational implications. We also note that these life-cycle processes occur on two physically different scales: macroscopic/MHD scales (MHD dynamo, MRI, collimation and acceleration of jets/winds, magnetic braking); and microscopic/kinetic plasma scales (collisionless shocks, reconnection, plasma micro-turbulence, non-thermal particle acceleration, radiation).

This white paper will highlight the following topics:
(1) The Origin of Magnetic Fields and Magnetic Activity in Stars
(2) Accretion Disks
(3) Stellar explosions: SNe and GRBs.

2 Stellar Magnetic Fields and Magnetic Activity

Magnetic fields are evident in all phases of stellar evolution. Not only are they directly measured in main sequence stars and white dwarfs, but their presence is also revealed indirectly through active stellar coronae, outflows, and the evolution of stellar rotation (e.g., in neutron stars). This raises the following broad unifying issues that we discuss in this section: the origin of magnetic fields in stars including the Sun; their dynamical role in stellar evolution; and the stellar coronal and outflow activity powered by magnetic dissipation.

2.1 MHD Dynamo and the Origin of Stellar Magnetic Fields

Global reversals of the solar magnetic field imply in situ field regeneration by a dynamo, and rule out a fossil field origin. However, understanding what the minimum ingredients for a dynamo are, how a dynamo grows fields of large enough scale to survive into the corona, and linking this field growth directly to stellar coronal activity comprise an enterprise of research. The subject demands understanding the interplay between convection, MHD turbulence, differential rotation, and stratification. The scale separation and the complex mutual interdependence of these processes requires a symbiosis between semi-analytic approaches parametrizing nonlinear features and carefully designed numerical simulations. Recent theoretical developments and evolving numerical tools bode well for substantial progress in this area in the next decade. Furthermore, advances in stellar dynamo will also impact our understanding of the origin of galactic, and accretion-disk, magnetic fields.

Dynamo action can be classified into two categories: (1) Small-scale dynamo in which magnetic fields are amplified at and below the driving scale and (2) Large-scale dynamo (LSD) in which an initially weak large-scale field is amplified with a sustained flux on time and/or spatial scales significantly larger than that of the turbulence. Large-scale dynamos are of particular interest in astrophysics since they are needed to explain the solar magnetic field and probably the origin of large-scale fields of any rotating convective star (including proto-neutron stars). The key unifying quantity in LSDs is a magnetic-field-aligned mean EMF.

A fundamental impasse with earlier LSD theories is that they were kinematic, and hence could not predict the saturation level of the large-scale field. Recently, however, new principles and their numerical tests have emerged, opening the door to progress: a unifying role of the magnetic helicity in LSDs has been recognized, with large-scale growth of one sign, and small-scale dissipation of the opposite sign. Coupling the dynamical evolution of magnetic helicity into the LSD equations has led to a semi-analytic nonlinear dynamo model for the large-scale field saturation [4], confirmed by numerical simulations [7]. Studies using open boundaries, convection, and shear, have also lent support to the paradigm that tracking the flow of the large- and small-scale magnetic helicity has predictive power [3, 23, 20]. Incorporating the principle of magnetic helicity evolution into more realistic global dynamo models and developing a practical "textbook" theory is a challenge for the next decade.

The MHD dynamo problem is intrinsically related to MHD turbulence, and the last decade has seen great progress in our theoretical understanding of this challenging subject [12, 13, 17, 5]. In a realistic turbulent system, small- and large-scale field amplification is often contemporaneous. While in the past LSD theory has often focused on field growth at the largest scale, turbulence approaches focus on the overall spectrum [7, 6], and so the

term “LSD” means the generation of magnetic fields on any scale larger than the turbulent scale.

Regarding future progress, recent numerical studies indicate that proper simulations of MHD dynamo (and MHD turbulence in general) must include small but finite *explicit* resistivity and viscosity corresponding to rather large Reynolds and magnetic Reynolds numbers, at least $10^3 - 10^4$. Although the required computing power has not been easily available in the past, it is now becoming common place. Thus, the application and further development of analytical theory combined with powerful numerical simulations gives us a unique opportunity to solve this important problem.

Finally, new liquid-metal and plasma laboratory experiments (existing and proposed) are underway to study flow-driven MHD dynamos under controlled conditions. Although these experiments cannot address the nonlinear saturation of LSDs, they can test the key basic principles of the kinematic dynamo, which so far have been assumed or tested only numerically. In addition, dynamos in magnetic-confinement plasma devices such as Spheromaks and RFPs, which describe the relaxation of strongly-magnetized systems to large scales in response to small-scale magnetic helicity injection, are directly related to field opening and relaxation in coronal plasmas. This analogy should be exploited.

2.2 Differential Stellar Rotation

Convectively driven dynamos in planetary cores and in the outer layers of late-type stars (e.g., the Sun) are associated with magnetized, *differentially rotating* flows. The origin of these differentially rotating flows is not well understood, but it is known that their stability is profoundly affected by even very weak magnetic fields, as is beautifully exemplified by the magneto-rotational instability (MRI) in accretion disks. An important clue is that recent helioseismology results and the vorticity equation together imply a near confluence of surfaces of constant angular velocity and constant entropy throughout the bulk of the solar convection zone. This, as has been recently noted [1], is just the expected configuration of a weakly magnetized, differentially rotating, convecting gas that is marginally (un)stable to “magneto-baroclinic” modes enabled by a weak magnetic field. Clearly, the consequences of MHD processes in rotating convective systems has yet to be fully elucidated.

2.3 Coronal Activity

Most of the stellar dynamo studies described above naturally focus on flow-dominated amplification of the magnetic field that takes place in the interiors of stars. However, the magnetic activity that we actually observe takes place in the stellar coronae. It is thus important to prioritize research that can make the connection between the fields produced inside a star and what emerges (due to magnetic buoyancy) into the corona. Similar arguments also apply to the coronae of accretion disks. Once in a star’s (or a disk’s) corona, the magnetic field structures are still evolving, in part towards the largest possible scales. Thus, the analogy between stellar dynamo, coronal fields, and the large-scale fields of coronal holes, and the accretion disc dynamos and the large-scale fields of jets should be pursued.

Whereas the dynamo regions where magnetic fields are generated are relatively dense and cold, the coronae of stars and accretion disks, where the field destruction actually takes place,

are hot and rarefied. Therefore, whereas resistive MHD is probably a good description in the former environment, it may not be valid in the latter. Thus, the life of magnetic fields is not limited to single-fluid MHD, but goes well beyond, into plasma physics proper, requiring a two-fluid or even a kinetic description. In particular, non-thermal particles and plasma microturbulence are likely to play an active role in the low-density collisionless or marginally collisionless coronal environments.

In this regard, we would like to stress the importance of recent advances in magnetic reconnection research, including theory, numerical simulations, and lab experiments. The emerging understanding of the role of plasma collisionality and of collisionless plasma processes is only now starting to percolate and to be applied in today's astrophysics, namely, to astrophysical coronae [22]. This work should continue since it may finally lead to understanding the principles governing these coronae and their emission.

3 Accretion disks

Accretion disks are essential to the formation, evolution, and observable radiation of many classes of stars and compact objects, including protostars and protoplanets, CVs, XRBs, and supermassive black holes. The process of accretion requires that mass be separated from angular momentum; understanding this angular momentum transport (AMT) has been a longstanding problem. There are good theoretical grounds for believing that AMT occurs via MHD turbulence driven by the MRI, though magnetized winds and jets are also candidate mechanisms. Magnetic and plasma processes clearly lie at the heart of accretion-disk dynamics. Recent numerical research indicates that the intensity of MRI turbulence may depend on many factors, e.g., under certain circumstances, on the microphysical dissipation coefficients [9]. Determining when MRI-turbulence in accretion disks is a self-sustaining dynamo is a very active area of research. A proper understanding of it will require very high-resolution 3D simulations with large values and ranges of Reynolds and magnetic Reynolds numbers. This should be feasible in the next decade.

One of the richest and most challenging applications of AMT studies is to cool disks, namely, protostellar disks and the outer parts of AGN disks. These media are characterized by small ionization fraction, high resistivity, and poor gas–magnetic field coupling. The ionization is governed by a poorly understood balance involving nonthermal ionization sources, dust physics, and molecular chemistry. The dominant ionization sources in protostellar disks are the coronal X-rays from the central star and Galactic cosmic rays [10, 11]; in AGN, it is probably the nonthermal hard X-ray emission from the inner disk. In all cases, understanding the nature of a magnetized hot plasma is central.

The difficult, longstanding problems raised above belong to the domain of MHD and kinetic plasma physics. The effort required to address is justified because the prospects for progress over the next ten years are good, and because an understanding of these processes is critical to problems at the forefront of astrophysics. Consider but two very important problems in modern astronomy: planet formation, and the joint evolution of galaxies and their central black holes. To understand the emergence of planets in a protoplanetary disk, for example, one has to know how the intensity of turbulence depends upon macroscopic disk parameters (e.g., density, temperature, and irradiation) and how the turbulence in turn

governs the rates at which dust settles, planetary cores grow, and planetary orbits migrate. In AGN, the microscopic exchange of energy among electrons, ions, and magnetic fields not only affects how we deduce accretion rates from observations, but also is critical to the balance between accretion and ejection, hence the feedback on the host galaxy.

What are the prospects for progress? First, MRI-driven turbulence, the most plausible fundamental reason why accretion in disks occurs, has now become a mature field of research. Although technically difficult, liquid-metal experimental studies of the MRI have already achieved greater hydrodynamical Reynolds numbers than are accessible to the most powerful numerical simulations, thereby placing rigorous limits on any non-magnetic turbulent transport in rotating flow [14]. With plausible increases in scale, these experiments could produce MRI turbulence in the important low magnetic Prandtl number regime. On the observational front, we expect that molecular spectroscopy and direct imaging of protostellar disks via ALMA and SOFIA will provide valuable results, constraining or determining disk densities, temperatures, ionization fractions, and chemistry. The prospects for a similar progress in X-ray studies of black-hole disks are less certain. However, there is a growing confidence among plasma physicists, based on numerical simulations and lab experiments, that the mechanisms for fast magnetic reconnection (presumably powering accretion-disk coronae) in collisionless plasmas have been identified.

The focus of accretion disk studies is now shifting from the classical AMT problem towards small-scale dissipation, detailed thermodynamics, and radiation in accretion flows. Important questions that will dominate this area in the next decade include the following: How and where is the turbulent kinetic and magnetic energy dissipated into heat to produce the observed emission? Does dissipation via reconnection occur in the collisional (resistive-MHD) or collisionless regime? What causes spectral-state transitions in accreting black holes? What fraction of the accretion energy is dissipated locally in the disk and what fraction in an overlying corona? How much energy goes into an outflow? How does the small-scale MHD turbulence interact with a large-scale external magnetic field? How is material transferred from the inner edge of a disk to a central, possibly magnetized, star?

In brief: the focus of accretion disk studies is shifting toward the physics of plasmas.

4 Gamma-Ray Bursts

4.1 GRB/SN Central Engines

Long Gamma-Ray Bursts (GRBs), perhaps the most powerful and enigmatic explosions in the Universe, are still only poorly understood. Are they associated with supernovae (SNe) or failed SNe? Are they powered by a hyper-accreting black hole, as in the collapsar model, perhaps via the Blandford-Znajek mechanism, or by a rapidly-rotating magnetar? What are their characteristic neutrino- and gravitational-wave signatures? How do their relativistic jets interact with the surrounding stellar envelope and collimate? Are they kinetic-energy-dominated (as in the traditional fireball/internal shock picture) or Poynting-flux dominated? How can one observationally distinguish between these alternatives?

In the past few years, traditional, purely neutrino-driven models of SNe and GRB have come into doubt. This has led to a growth of interest in magnetically-driven core-collapse

explosions of massive stars, in which the central engine's rotational energy is extracted magnetically to power the explosion (e.g., via a magnetic-tower-like mechanism). In fact, this general mechanism is applicable to a broad class of asymmetric stellar explosions/outflows, e.g., to planetary nebulae — the end states of low-mass stars [2].

Future theoretical progress in understanding the central engines of SNe and especially GRBs will require a better grasp of basic plasma physics relevant to this extreme, high-energy-density environment. Thus, assessing the dynamical role of magnetic fields makes the task of understanding the classical MHD processes (dynamo, MRI, magnetic towers, jet acceleration and collimation, Parker and kink instabilities, reconnection) in the context of collapsing stars, imperative. Significant numerical progress in this area is expected in the next decade due to the advent of general-relativistic MHD codes employing advanced numerical algorithms and incorporating realistic microphysics (including neutrino processes), combined with the ever-increasing computer power.

4.2 Collisionless Shocks, Radiation, and "a GRB in a Lab"

Even if initially the jet is magnetically dominated, in the end one still has to understand how the jet energy is eventually converted to the observable radiation. There are, in principle, two main ways of doing this. One is the classical *internal shock model*: slow, macroscopic magneto-centrifugal acceleration gradually converts the Poynting flux to the bulk kinetic energy of the relativistic flow, which is later dissipated in microscopically-thin collisionless shocks producing nonthermal electrons that subsequently radiate away their energy. In the other case, a magnetically dominated jet may undergo direct, microscopic dissipation via reconnection in current sheets produced by MHD instabilities or by initial irregularities in the jet; non-thermal particles accelerated in the reconnection region then produce the observed emission. Both of these scenarios involve collective plasma processes at microphysical scales (plasma microturbulence) coupled with nonthermal particle acceleration and radiation. We shall now discuss the first (more widely accepted) scenario in more detail.

GRBs are the most extreme end of cosmic blast waves, and their detailed physical understanding has to be based on the merger and interpenetration of astrophysics and plasma physics (namely, high-energy-density and relativistic plasma physics). The past decade illustrated the fruitfulness of such a process, as we went from the first theoretical realization of the importance of the Weibel instability (a kinetic anisotropy-driven plasma instability) for the formation of GRB collisionless shocks [15] to breathtaking kinetic plasma simulations [18, 8, 19], and we are now about to produce Weibel-mediated shocks with nearly realistic (astrophysical!) plasma conditions on Earth with Petawatt-scale lasers. The traditional picture of GRBs holds that they launch ultra-relativistic (with Lorentz factors $\sim 10^2$) outflows that produce relativistic collisionless shocks both inside the outflow and at the ambient medium interface. At such shocks, the plasma (unless strongly magnetized) breaks up into an array of small-scale current filaments via the Weibel instability, generating strong magnetic fields. The resulting nonlinear plasma turbulence scatters particles, effectively introducing collisions into the otherwise collisionless plasma. Moreover, radiation emitted by the shock-accelerated electrons in such sub-Larmor-scale magnetic fields is markedly non-synchrotron. A radiating electron never completes its gyro-orbit but, instead, jitters around its nearly straight trajectory, possibly accounting for the observed benchmark harder-than-

synchrotron “jitter” radiation spectrum [16].

While the general picture seems to be understood, many questions remain open. What is the dynamics of the nonlinear Weibel turbulence in the upstream precursor and the downstream post-shock plasmas? How does this turbulence heat the electrons? What role do the Weibel fields play in Cosmic Ray (CR) acceleration? What feedback do the CRs exert on the shock by modifying the upstream medium? How is radiation produced in Weibel-mediated shocks? All these questions are crucial for our understanding of GRBs.

Most of the present-day results come from extensive PIC simulations. This line of research will grow as Petaflop-scale computers become available, which will enable us to model 3D ion-electron collisionless shocks, including radiation production and CR acceleration, with the level of detail that is now achieved in 2D electron-positron shock simulations.

The Weibel instability will also be studied in lab experiments at modern Petawatt-scale laser facilities such as NIF, Omega EP, Hercules, PW, and Ghost. These lasers can produce relativistic electron beams with Lorentz factors of $\sim 10^2$, similar to those in GRBs, and the Weibel turbulence has already been observed in some laser-plasma experiments [21]. Therefore, the very possibility to experimentally explore the turbulence with good diagnostics is already at our disposal. Radiation mechanisms can be probed as well, since the predicted jitter radiation peaks at a few keV and can be diagnosed with standard X-ray detectors. Amazingly, the laser-plasma parameters are very similar to those in GRB shocks, setting a characteristic length-scale (plasma skin depth) to be $\sim 10\ \mu$m in laser plasma and a few mm in GRBs. Apparently, not much scaling is needed between astrophysical phenomena and lab experiments. Producing a Weibel-mediated collisionless shock, which requires a few hundreds skin lengths to form, is clearly a feasible experiment with a typical cm-size target. Lighting up a GRB in a lab – what can be more fascinating than this!

References

[1] S. Balbus, eprint arXiv:0809.2883 (2008)

[2] B. Balick & A. Frank, ARA&A, 40, 439 (2002)

[3] E. Blackman & G. Field, ApJ, 534, 984 (2000)

[4] E. Blackman & G. Field, PRL, 89, 265007 (2002)

[5] S. Boldyrev, ApJ, 626, 37 (2005)

[6] S. Boldyrev et al., PRL, 95, 255001 (2005)

[7] A. Brandenburg, ApJ, 550, 824 (2001)

[8] J. Frederiksen et al., ApJ, 608, L13 (2004)

[9] S. Fromang et al., A&A 476, 1123 (2007)

[10] C. Gammie, ApJ 457, 355 (1996)

[11] A. Glassgold et al., ApJ 340, 484 (1996)

[12] P. Goldreich & S. Shridhar, ApJ, 438, 763 (1995)

[13] P. Goldreich & S. Shridhar, ApJ, 485, 680 (1997)

[14] H. Ji et al., Nature 444, 343 (2006)

[15] M. Medvedev & A. Loeb, ApJ, 526,697 (1999)

[16] M. Medvedev, ApJ, 540, 704 (2000)

[17] H. Politano & A. Pouquet, PRE, 57, R21 (1998)

[18] L. Silva et al., PRL, 92, 015002 (2004)

[19] A. Spitkovsky, ApJ, 682, L5 (2008)

[20] S. Sur et al., MNRAS, 377, 874 (2007)

[21] M. Tatarakis et al., PRL, 90, 175001 (2003)

[22] D. Uzdensky, ApJ, 671, 2139 (2007)

[23] E. Vishniac & J. Cho, ApJ, 550, 752 (2001)